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Aerobraking Automation Options

by

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Abstract:

Two interplanetary missions have successfully used aerobraking to provide a velocity change of 1200 m/s. The first was the Magellan mission to Venus, where atmospheric drag was used to shrink the orbit late in the extended mission. The second was the Mars Global Surveyor (MGS) mission to Mars. Both of these missions required extensive commanding from the ground in order to keep the activities on the spacecraft, especially those during the pass through the atmosphere, synchronized with the actual orbit. This paper will summarize some recent work to automate most of the commanding intensive activities associated with aerobraking.

Introduction:

Aerobraking means making multiple drag passes through an atmosphere in order to gradually remove energy from an initially elliptical orbit. The aerobraking phase of both the Magellan and Mars Global Surveyor missions were very similar in many respects. Both used aerobraking to shrink an initially elliptical orbit down to a nearly circular orbit. Both missions were propulsively captured into orbit and both used the drag from multiple passes through the atmosphere to remove about 1200 m/s from the orbital velocity. Frequent commanding from the ground was needed to update timing parameters in order to keep the on-board timing synchronized with reality. This frequent, critical commanding put a strain on both the Deep Space Network (DSN), which had to uplink the commands, and the Flight Team, which had to evaluate the telemetry and tracking quickly in order to create a new set of commands.

This paper will first describe how aerobraking operations were conducted in the past, and will then explore some options for automating some of these activities in order to reduce the strain on both the DSN resources and the Flight

Team sanity. The initial phase of the research will show that the activities that occur every orbit can easily be automated using the same sequence of commands every orbit as long as the start time is computed on-board the spacecraft.

The predictive requirements are fundamentally different for very long and very short orbit periods. Longer period orbits are much more sensitive to drag, because a small ΔV at periapsis can change the orbit period by hours. Atmospheric density uncertainties make it difficult to predict the drag ΔV in advance. Thus, longer period orbits require accelerometer measurements to actually measure the drag ΔV on one pass in order to predict the change in orbit period and establish the time of entry for the next pass. Smaller period orbits are much less sensitive to uncertainty in the atmospheric drag, because the change in the orbit period is very small. Since several orbits are required for the timing error to build up to undesirable levels, the sequence of events for a small period orbit can be automated by simply sensing an event that is tied to the drag pass and resetting the timing each orbit. The robustness of the timing algorithms can be enhanced by using a new reaction wheel control law which increases the available timing margin while eliminating unnecessary thruster firings, including those required for reaction wheel desaturation.

Aerobraking activities can be broken into two major categories: Sequencing and Corridor Control. Since the proposed algorithms automate only the sequence timing, but not the propulsive maneuvers to maintain the periapsis altitude in the desired corridor, they are "Semi-Autonomous" algorithms. Options for fully automating operations during aerobraking are being studied and will be reported in the future.

Magellan, the First Aerobraking Mission:

On Aug. 3, 1993, the Magellan spacecraft became the first mission to successfully use aerobraking to deliberately change the orbit of an interplanetary spacecraft from an initially elliptical capture orbit to a nearly circular science orbit.[1-10] Before aerobraking was attempted, Magellan completed the primary mission to obtain a global radar map of the planet Venus and had mapped as much of the gravity field as the initial 3.24 hour elliptical capture orbit would allow. In order to obtain a global gravity map at the highest possible resolution, the orbit had to be circularized by reducing the orbital velocity at periapsis by 1,200 m/s. Since the remaining propulsive capability was only about 100 m/s, aerobraking was the only means available to circularize the orbit. Since the Magellan spacecraft was not designed to dip into the atmosphere, the flight team was not at all certain that the spacecraft would be able to survive the aerobraking phase. The project was able to attempt aerobraking in spite of the risk because the Magellan spacecraft was rapidly approaching the end of its useful life.

The flight software was modified so that the same sequence of events could be repeated over and over in order to minimize the workload on the already "lean-mean" operations team. The sequence timing for each orbit was specified relative to the start of the sequence, which was many minutes before periapsis. A small set of parameters were uploaded periodically to shift events in the orbit. For example, the optimum time to perform a small propulsive maneuver to adjust the altitude of periapsis is at apoapsis. As the orbit period shrank, the time from the start of the sequence to the time of the propulsive maneuver had to be reduced about once a week. Although the parameter values that specified the time of events, such as the propulsive maneuver, relative to the start of the sequence for Magellan was changed only by ground command, these parameter changes could easily be computed on-board in order to maximize the interval of autonomous operation.

The Magellan aerodynamic moments were very large, so the spacecraft could not maintain the normal Earth pointed attitude during the drag pass near periapsis. The spacecraft was commanded into a "tail-first", aerodynamically stable attitude before the start of the drag pass so that the control system would not waste propellant trying to fight the overwhelming aerodynamic moments. The spacecraft was returned to an Earth pointed attitude following the end of the drag pass in order to use the higher data rate from the High Gain Antenna. Since the times of these drag related events were specified by parameters that were predicted and uploaded from the ground, they had to be updated about once per day to keep the timing error less than the 5 minute timing margin that was included on each side of the drag pass. A 5 minute margin meant that the spacecraft ended its turn to the drag attitude 5 minutes before the predicted time of atmospheric entry, and it maintained the drag attitude for 5 minutes after the predicted time of atmospheric exit.

A daily update of the key timing parameter, the change in orbit period per orbit, was possible for the Magellan spacecraft for three reasons. First, the periapsis altitude drift was very predictable. The longitude of periapsis was nearly the same from one orbit to the next because Venus rotates very slowly, so the gravitational perturbation was nearly the same. Second, the density of the atmosphere was very predictable from one orbit to the next, only varying by about 6% (1-sigma). Finally, the initial orbit period at the start of aerobraking was already very small, a little over 3 hours, so the 5-12 sec change in the orbit period was small enough that the timing error had to accumulate over several orbits before it became significant. Unfortunately, none of these three factors prevail at the start of most Mars aerobraking missions.

While in the drag attitude, the Magellan spacecraft attitude was controlled by the thrusters in order to accommodate the error in the reference attitude caused by the uncertainty in the orbit timing. A very important reason for choosing this approach was to save cost by using existing control modes, with a few parameter changes, because costly changes to flight software were minimized. By giving the thruster control system a large (17°) deadband, and allowing the aerodynamics to drive the attitude toward the aerodynamically stable attitude, the spacecraft could pass through the atmosphere without wasting large amounts of propellant fighting the aerodynamic moments. A timing error of about 5 minutes was equivalent to a 17° change in the reference attitude. If the timing error were larger than 5 minutes, then the aerodynamically stable attitude would be "outside" the deadband relative to the reference attitude, and the thrusters would fire in a futile attempt to drive the attitude back inside the deadband. Although a single orbit with a moderate timing error a few minutes larger than the margin would waste some propellant, it would not be catastrophic to the mission.

The 5 minute timing margin was the result of the decision to use a reference attitude that varied as a function of the time since periapsis on each drag pass. The time varying reference attitude was periodically updated to accommodate orbital precession. Although the wide thruster deadband and the initially short drag duration meant that an inertial reference attitude could have been used during most of the aerobraking phase, where the attitude change during a drag pass was smaller than the deadband, the attitude change near the end of aerobraking grew to nearly 90°, which was much larger than the value that could be accommodated using an inertial reference attitude and a 17° deadband. The project decided to use a time varying reference for the entire aerobraking phase to reduce the development workload on the flight team, which did not have the manpower to develop two flight qualified reference attitude algorithms.

Unfortunately, the gyros in the inertial measurement unit which were used to propagate the attitude on Magellan would lose track of the spin direction if the spin rate became too large. Very large timing errors could result in the loss of the spacecraft because the angle of attack at entry is proportional to the timing error when the attitude reference is time varying. The attitude rates that could be induced by a very large angle of attack at atmospheric entry were larger than the Magellan gyros could accommodate. Future aerobraking missions should always use gyros that do not lose track of the spin direction when saturated!

One additional aspect of the Magellan reaction control mode should be mentioned. The Magellan spacecraft was designed to fly using reaction wheels for attitude control, except during propulsive maneuvers. When the spacecraft switched to thruster control, the reaction wheels were uncontrolled and gradually spun-down due to friction in the bearings. The angular momentum stored in the wheels was gradually transferred to the spacecraft, which slowly rotated toward the boundary of the 17° deadband, where the thrusters were fired to change the direction of the slow spacecraft rotation. With a five minute margin, there was usually time for the spacecraft to "bounce" off one side of the deadband before entering the atmosphere. Once in the atmosphere, the aerodynamics controlled the attitude, although the relatively large angle of attack at entry resulted in a relatively large amplitude oscillation about the aerodynamically stable attitude.

An evaluation of the Magellan system lead to the following option, which should be considered for use on future aerobraking missions. Using the reaction wheels for attitude control during the drag pass would have eliminated these large attitude oscillations by enabling the spacecraft to enter the atmosphere at a known inertial attitude with a small angle of attack that would be independent of the timing error. Such a reaction control mode would also increase the robustness of aerobraking by increasing the 5 minute timing margin to a larger value. The entry attitude is well known in advance. Only the time of entry is uncertain when trying to predict several orbits into the future. The spacecraft could have been turned to the inertial entry attitude and could have maintained this attitude "indefinitely" until atmospheric entry was sensed, at which time the reaction wheels could have been commanded to drive the system angular momentum toward zero (to desaturate the wheels for free). This possibility will be discussed later in the paper.

Mars Global Surveyor, the Second Aerobraking Mission:

On Feb. 4, 1999, Mars Global Surveyor became the second interplanetary spacecraft to successfully aerobrake from an initially elliptical orbit into a nearly circular final science orbit.[10-13] Unlike Magellan, the Mars Global Surveyor spacecraft was designed to aerobrake. The cell interconnects on the solar panels were welded, rather than soldered, and the bonding adhesives were selected to maintain strength at high temperatures. Some of the paint patterns on the solar panels were chosen to provide additional thermal inertia near the leading edges of the solar panels where the aerodynamic heating was predicted to be the largest. These changes increased the qualification temperature limit to 190° C, although the flight allowable limit was 15°C less than the qual limit. (The Magellan temperature limit was 160 °C).

Many of the aerobraking procedures were inherited from Magellan. For example, thruster control with a large (20°) deadband was used during the drag pass to emulate the procedure used by Magellan. A time varying reference attitude was also used, which resulted in about the same deadbands and timing margins. The MGS control system design included a rate term that was missing in the Magellan design in order to provide damping after the spacecraft left the atmosphere.

Many activities have to occur during a typical aerobraking orbit. Figure 1 shows the sequenced activities during a typical aerobraking orbit from the Mars Global Surveyor mission. Because the aerodynamic torques during the drag pass can be much larger than the control authority of either the reaction wheels or the thrusters, the spacecraft must be properly configured for the drag pass and commanded to an attitude which will minimize the aerodynamic torques before the spacecraft enters the atmosphere. Since the drag pass is nearly centered about periapsis, the predicted time of periapsis is a convenient reference time for each orbit, even though some events occur before periapsis.

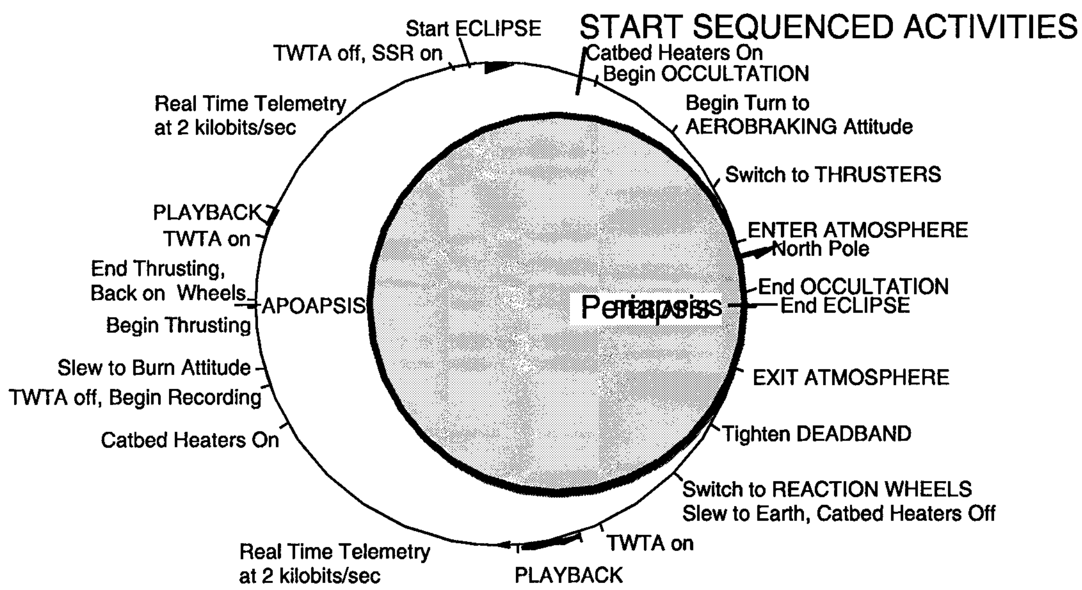

Figure 1: Sequenced Activities & Key Events for a Typical MGS Orbit

The activities on-board the spacecraft were specified by a "sequence" of time-tagged commands that were built on the ground and uplinked to the spacecraft. Using the typical MGS orbit in Figure 1 as an example, the first command in the sequence for each aerobraking orbit was the command to turn on the catalyst bed heaters, which warmed the thrusters prior to use to minimize damage when they were fired later. The next command was a maneuver using reaction wheels to slew the spacecraft into an attitude close to the desired attitude at atmospheric entry. Any required reconfiguration of the spacecraft occured at about the same time as the slew maneuver. Both Magellan and MGS had to place the solar panels in a specific configuration to maximize the drag, while maintaining an aerodynamicallys stable, tail-first attitude. Before atmospheric entry, the spacecraft attitude control mode was switched from a reaction wheel control mode to a thruster control mode with a wide deadband so that the attitude control system would not waste propellant trying to fight the aerodynamic torques, which dominate during the drag pass. After exiting the atmosphere, the spacecraft attitude control was switched back to reaction wheel control, the spacecraft was reconfigured, and the attitude was slewed to point the High Gain Antenna at the Earth to playback the data recorded during the drag pass. The beginning and ending times of the playback were specified by the sequence.

During the exo-atmospheric portion of the orbit, the spacecraft remained Earth pointed until just before the next drag pass. The sequence of commands for the next orbit repeated the same set of commands, starting with the command to turn on the cat-bed heaters in the thrusters. On MGS, the uplinked sequence contained the set of commands for several orbits. Even though the set of commands for each orbit were the same except for the execution time-tag, the MGS sequence was built as one big list, rather than as a "loop" which called a "subroutine" repeatedly, once for each orbit. (The "looping" approach was used on the Magellan mission, although timing updates were uplinked from the ground, rather than computed on-board.)

Although sequences are built on the ground and uplinked to all interplanetary spacecraft, this process is particularly challenging during aerobraking because unpredictable atmospheric fluctuations result in unpredictable changes in the actual times of periapsis. An uplinked sequence that is built on the ground using predicted times rapidly gets "out of phase" with the actual location of the spacecraft on the orbit due to the differences between the predicted and actual drag values on the preceeding orbits. Mars Global Surveyor, for example, required a new sequence upload every orbit when the orbit period was larger than about a day. Near the end of the planned aerobraking phase, when the orbit period was only 2 hours, three sequence uploads per day were expected, just to keep the sequence timing within the 5 minute limits. Multiple orbit predictions become possible for the shorter orbit periods because the change in orbit period per orbit for the same drag-induced velocity change is smaller. For an orbit period close to 2 hours, the nominal change in the MGS period per orbit was less than 30 seconds. For the 45 hour orbit period at the start of the MGS aerobraking phase, the planned change in orbit period was several hours per orbit. The 30% (1 sigma) atmospheric variability meant that the <u>uncertainty</u> in the predicted time of periapsis could be close to an hour for the larger period orbits. The timing predictions had to be updated after each drag pass so that the sequence would command the spacecraft to the drag attitude within 5 minutes of atmospheric entry. This paper will show that the MGS time of periapsis could have been predicted to within 90 seconds using the accelerometer data, even for the larger period changes associated with the larger period orbits.

Differences between MGS & Magellan:

Some orbits require a propulsive maneuver near apoapsis, to raise or lower periapsis to achieve the desired amount of drag and heating during the next drag pass. On Magellan, the on-board sequence checked a flag on even numbered orbits to determine which, if any, of a previously loaded set of 8 maneuvers would be performed at a parameterized time since periapsis. The maneuver flag was set by ground command and uplinked prior to the actual maneuver to chose which of the 8 possible maneuvers would be triggered. Thus, only a single byte of data had to be uplinked to Magellan to trigger a so-called "corridor control" maneuver. For a future aerobraking Mission to Venus, automating this trigger on-board the spacecraft would be fairly straightforward, since the atmospheric variability observed by Magellan was only about 6% (1-sigma). Corridor control maneuvers are needed to remove long term changes in the periapsis altitude caused by gravitational and solar perturbations. The Mars Global Surveyor project thought that using the standard sequencing procedure would be cost effective not only for the corridor control maneuvers, but also for the aerobraking sequences. Thus each maneuver sequence was built on the ground, using a maneuver sequence template, and the entire sequence was uplinked for each maneuver. The MGS maneuver strategy is not suitable for automation on-board. The Magellan technique for triggering maneuvers could be used to automate the corridor control maneuvers, while the MGS approach was designed to require commanding from the ground. Unfortunately for aerobraking missions to Mars, MGS observed a 30% (1-sigma) random variability in the atmosphere. Furthermore, unpredictable dust-storms can change the atmospheric density at aerobraking altitudes near 120 km by an order of magnitude in a matter of days. The large, highly unpredictable atmospheric variability at Mars makes automation of the corridor control maneuvers a more difficult task than for missions to Venus. Deciding when to perform corridor control maneuvers for Mars aerobraking missions is still a challenging task for an experienced flight team which is better able to respond to changing conditions. The task of automating the maneuvers becomes possible if the difference between the nominal dynamic pressure required to achieve the mission objectives is significantly less than the dynamic pressure limit where the spacecraft would be damaged. MGS required the "nominal" dynamic pressure to be less than half the limit in order to accommodate the 30% atmospheric variability.

Some other differences between Magellan and MGS are: the velocity at periapsis, the gravitational perturbations, and the availability of accelerometer data.

Venus is a much larger planet than Mars, and has a much larger gravitational attraction. Thus the orbital velocity at Venus is approximately twice the orbital velocity at Mars. Since the aerodynamic heating rate is proportional to the cube of the velocity, while the drag is proportional to the square of the velocity, equal limits on the heating rate at Venus and Mars would imply that the dynamic pressure at Mars would be twice that at Venus. Unfortunately, the larger atmospheric variability at Mars requires the nominal dynamic pressure to be about half the maximum, so that the typical dynamic pressures are about the same when aerobraking at Venus or Mars, while the typical aerodynamic heating rate at Mars is about half that at Venus.

The gravitational perturbations at Venus and Mars are similar in that the periapsis altitude tends to drift either up or down for many consecutive orbits, requiring periodic corridor control maneuvers to maintain the desired level of drag. Since Venus rotates very slowly, a spacecraft in a highly inclined orbit always passes over the same general longitude for many consecutive orbits, no matter what the orbit period. Since Mars rotates about its axis once per day, a spacecraft orbiting Mars usually passes over a different longitude on Mars each orbit, which means that the perturbation on the periapsis altitude is different from one orbit to the next. Thus the orbit-to-orbit variability in the periapsis altitude of a Mars orbiter is much more random than for a Venus orbiter. This altitude variability is important during aerobraking, because the atmospheric density is an exponential function of the altitude, so small changes in altitude can have a significant effect on the density predictions. Solar perturbations can also have a significant perturbing effect on the periapsis altitude.

The Magellan spacecraft did not carry an accelerometer, so there is no accelerometer data to characterize the Venus atmosphere during aerobraking. The Mars Global Surveyor spacecraft did carry an accelerometer,[14] but only because it was part of the Mars Observer Inertial Measurement Unit that was inherited by the MGS design team. If anything has been learned from these previous aerobraking missions, it is that an accelerometer is invaluable not only for characterizing the atmospheric environment, but also as a critical measurement for automating various sequencing and telecommunications tasks associated with aerobraking. All aerobraking missions should be required to carry and use accelerometers.

Areas of Study:

Recent work to automate aerobraking has been in three major areas: accelerometer based prediction of the time of the next periapsis using <u>simple</u> to moderately complicated algorithms,[15] prediction of the time of the next periapsis using a full-up, traditional <u>navigation calculation on-board</u> the spacecraft,[16] and a modification of the <u>attitude control algorithm</u> that would enable a much larger timing margin.[17] A reaction wheel attitude controller that can increase the timing margin by switching autonomously from "inertial hold" to "atmospheric mode" could be used in conjunction with either the simple algorithm or on-board navigation approaches to improve the robustness of those approaches. It could also enable the "time-of-periapsis" update approach to work for a much larger range of orbit periods

The time of periapsis is used as the reference time, because it is a standard navigation product that is near the center of the drag zone, and because it is independent of margins or other considerations that might be part of the sequence timing. Furthermore, the time of periapsis is an observable event that can be inferred autonomously on-board the spacecraft. The actual start of the sequence of activities is normally computed as an offset from the time of periapsis.

Big Orbit Period vs Small Orbit Period:

The initial orbit period has a significant effect on the available automation options. For example, Magellan was propulsively captured into an orbit with a 3.24 hour period. The maximum change in the Magellan orbit period in one orbit was only 12 seconds. MGS, on the other hand, was propulsively captured into an orbit with a 45 hour period. The maximum change in orbit period in one orbit was 1.6 hours. Whether the orbit period is large or small, each drag pass changes the orbital velocity by several meters-per-second, but the change in orbital period is large when the orbital period is large and small when the orbital period is small.

For short orbit periods, the "time" can be adjusted each orbit by simply detecting an event associated with the drag pass and then using the current orbit period (the time between two events) to predict the time of the next event. The event detector can be a thermocouple that detects the temperature increase during a drag pass, an accelerometer that measures the deceleration spike during a drag pass, or even an attitude control system that detects the externally applied moment that drives the spacecraft toward the aerodynamically stable attitude. For example, Magellan could have used the thermocouples to detect the temperature rise during the drag pass, although the algorithm would have to have been designed to only search in a window centered on the predicted time of periapsis to avoid the temperature increase associated with exiting from eclipse. A more robust algorithm would have been to remain on reaction wheel control and use the angular momentum increase induced by aerodynamic moments to detect atmospheric entry.[17] Neither of these methods were tried for two reasons. First, the Magellan aerobraking experiment was done at the end of the mission on a very limited budget with a small staff, so there were insufficient resources available to develop and test the additional flight software that would have been needed. An equally important reason was that the project was not sure exactly how the spacecraft would react during aerobraking, so the spacecraft timing was updated from the ground, even though the sequences were implemented as a loop that would have been perfectly suited for automation. Analysis of the data after the fact shows that the sequence could have been automated by updating the timing on-board each orbit.

When the orbit period is large, changing the velocity at periapsis by several m/s can change the orbit period by hours. The only way to predict the next time of periapsis autonomously is to have some real time information, such as accelerometer measurements, which can be used to calculate the change in orbit period. Two approaches have been studied: a simple approach to estimate only the change in the orbit period and a complicated approach that does the full orbit determination on-board.

The Simple Approach:

The Simple Approach only tries to estimate the next time of periapsis in order to be able to start the sequence of events for the next orbit at the appropriate time. The best way to do this is to have an accelerometer on-board the spacecraft that can measure the deceleration due to the drag. The time of the current "periapsis" is computed by finding the "center of the drag pass", where half the deceleration has occurred. The time of the next periapsis is computed by integrating the deceleration during the entire drag pass to get an equivalent ΔV, and then using a polynomial function of the orbit period to determine how much the period will change if that ΔV were applied at periapsis. The current value of the orbit period is computed by computing the time between the center of the previous drag pass and the center of the most recent drag pass. Obviously, these computations cannot be done until after the spacecraft has left the atmosphere.

To illustrate how the "center of the drag pass" would be computed on-board the spacecraft, consider Figure 2, which shows the density versus time since periapsis that was inferred from the MGS accelerometer data for orbit 1094. The time of periapsis is from the navigation team orbit reconstruction made from tracking data taken before and after each drag pass. Two curves are shown: the jagged (blue) curve is a 6 second running mean of the accelerometer data (converted to density based on the spacecraft drag coefficient and velocity), whereas the smoother (red) curve is a 40 second running mean of the same data.

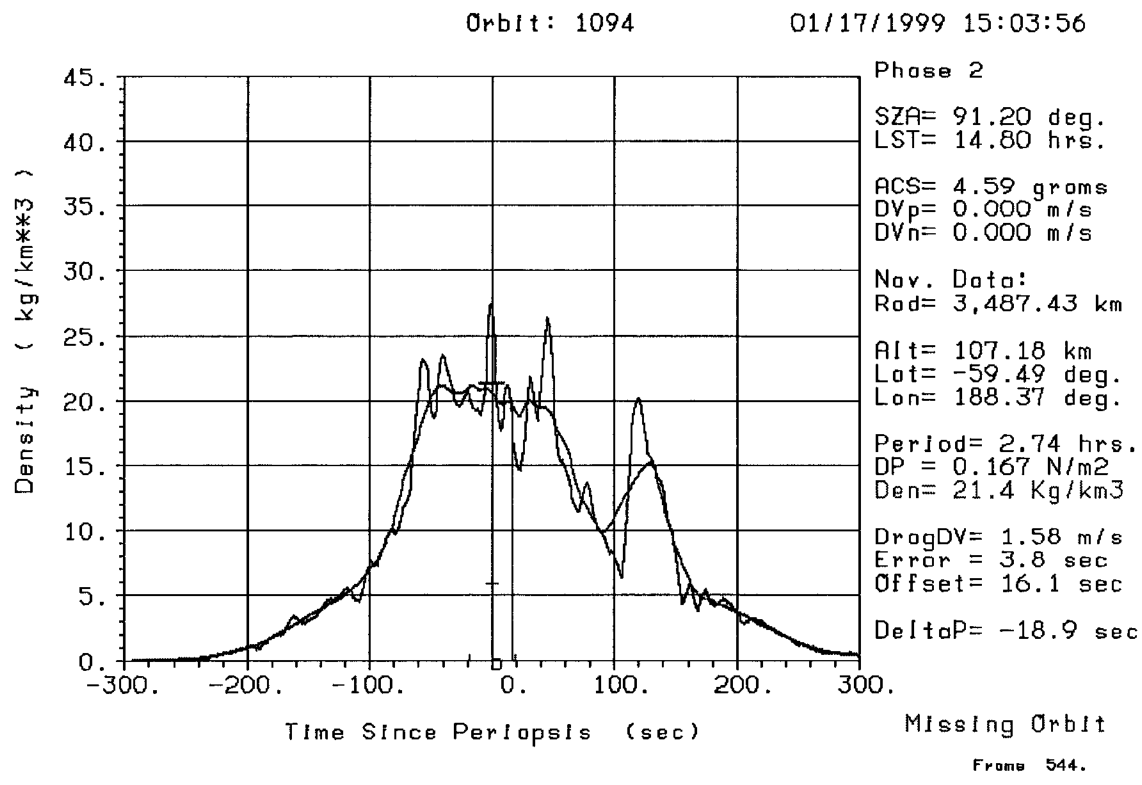

Figure 2: Example of an actual Drag Pass: MGS Orbit 1094

Computing the "center of the drag pass" by finding the "center of the integral" is necessary because the unsmoothed, raw accelerometer measurements are much noisier than the smoothed data, which may have multiple peaks in both the 6 second and 40 second data. Imagine what the multiple peaks in Figure 2 would do to an algorithm that was trying to find a single peak near periapsis! (Some MGS orbits have well defined peaks that are skewed from periapsis due to possible wave activity. Some MGS orbits do look "normal", with smooth, single peaks near periapsis.[18])

In Figure 2, the vertical line segment about 16 seconds to the right of periapsis divides the area under the (40 sec) curve in half. This line represents the best method to compute the "center of the drag pass" from the accelerometer data, because it always produces a time near the center of the drag pass. Note that because Mars has an equatorial bulge, and periapsis is usually not over the equator, the center of the drag pass would not normally be at periapsis, even for an ideal exponential atmosphere.

The altitude of periapsis during the aerobraking phase only changes by a few kilometers because propulsive maneuvers are used to keep the altitude in a corridor that is defined by dynamic pressure or heating rate. By assuming a constant periapsis altitude, the change in orbit period per meter/sec of drag ΔV can be computed for a conic orbit as a function of the orbit period before the spacecraft is even launched. A 10 km change in the assumed constant periapsis altitude changes the period prediction by a maximum of about 5 sec/m/sec, so a slightly better approach would be to use the expected periapsis altitude for a given mission, rather than the constant (120 km) used here. A cubic fit of the delta-period per m/s of drag ΔV versus orbit period provides a sufficiently accurate representation to store on-board the spacecraft for autonomous computation of the next time of periapsis. Since the drag pass is spread over a finite amount of time, the actual change in the velocity at periapsis is not quite as large as if all of the drag occurred at periapsis. (This lower efficiency is similar to the "gravity loss" during a finite propulsive capture.) A more accurate prediction is possible if a fudge factor is used to reduce the predicted period change by a few percent to account for the finite nature of the drag.

The Predicted Period Change = FUDGE * F(period_hrs) * DragDV {sec}

Where

FUDGE = 0.96 (Best Fit Fudge Factor to account for Finite Duration.)

$F(X) = -7.097 + 5.4596 * X + 0.8577 * (X^2) - 0.00361 * (X^3)$ {s/(m/s)}

X = Orbit Period, measured in hours

DragDV = Integral of Unbiased Accelerometer Measurements {m/sec}

The simple algorithm described above was used to predict the time of the "next periapsis" for all MGS aerobraking orbits which had archived accelerometer data. These predicted times were compared to the actual times that were reconstructed from the tracking data by the Navigation team. Figure 3 shows the prediction error for all 630 orbits in the MGS accelerometer data archives (some aerobraking orbits are missing from the archives for various reasons). Figure 3 shows that this very simple algorithm can be used to predict the time of the next periapsis with sufficient accuracy to meet the 5 minute timing accuracy used for MGS, even for the larger orbit periods.

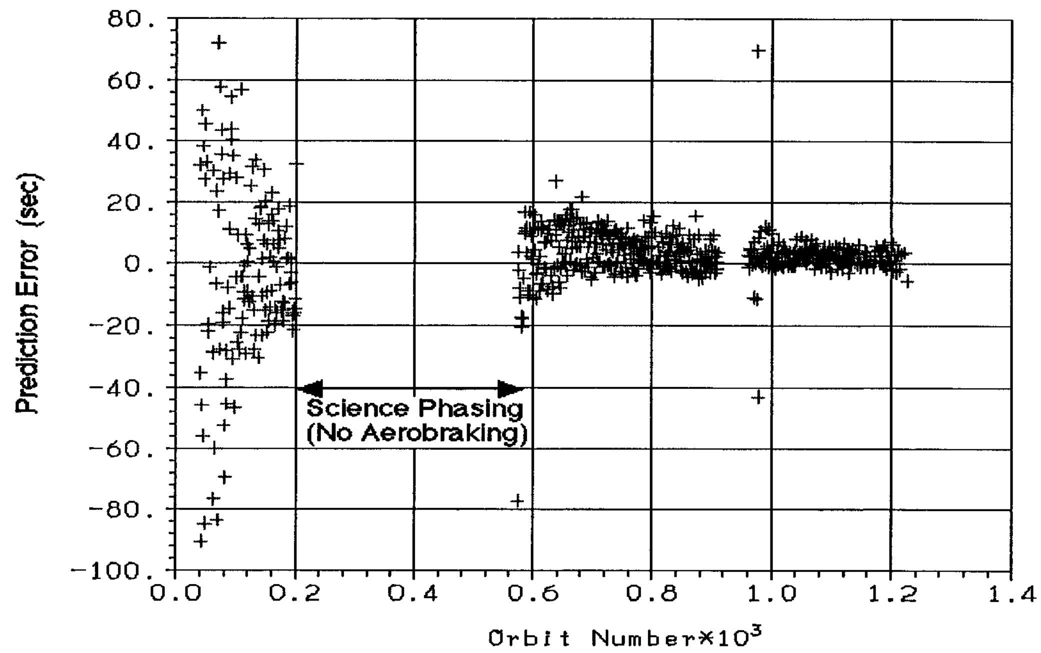

Figure 3: Periapsis Prediction Accuracy using the MGS Accelerometer Data

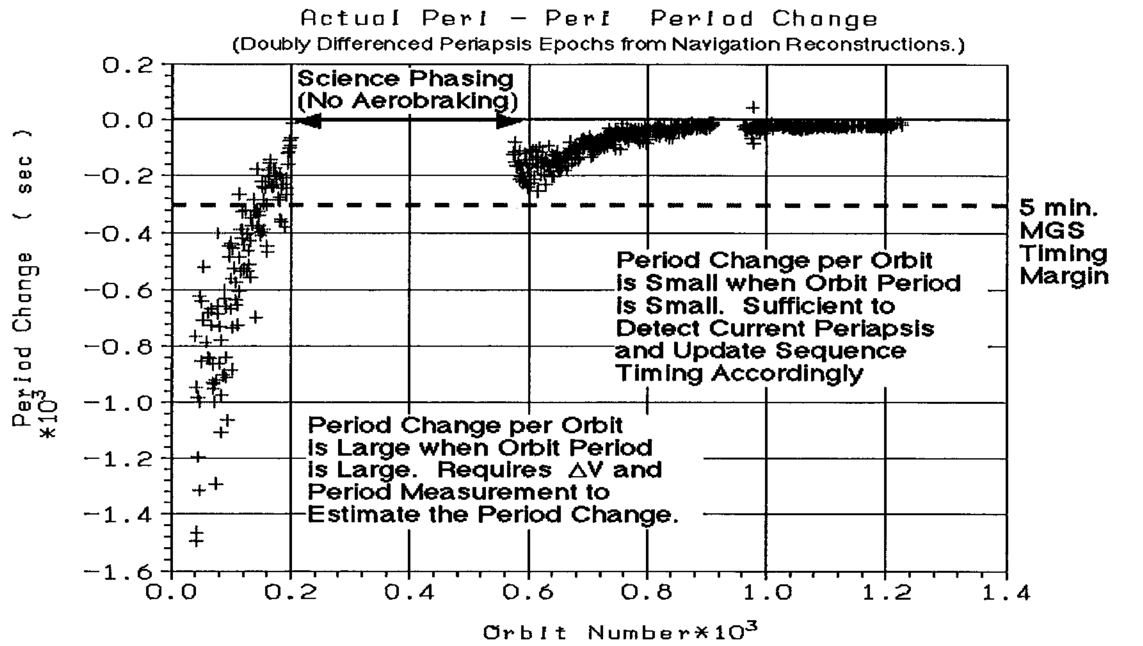

Figure 4: Actual MGS Orbit Period Change (Double Differenced Navigation Epochs)

Figure 4 shows the actual period change. The prediction error in Figure 3 is largest when the actual period is large, but in all cases, the prediction error is a small percentage of the actual period change.

Since the actual MGS dynamic pressures were reduced to about half the planned levels because one of the solar panels was broken, the prediction accuracy for a healthy spacecraft might be double that shown in Figure 3 if the Dynamic Pressures were double. Even with a larger dynamic pressure limit, the maximum timing error could still be predicted with an error less than 3 minutes. (The reaction wheel control mode that is discussed later can be used to increase the 5 minute limit.) Thus, this simple timing prediction algorithm provides the simplest, most cost effective way to automate the sequence timing.

Accurately determining the accelerometer bias is essential for accurately predicting the time of the next periapsis. On MGS, the bias was as large as the measurement! Fortunately, the MGS accelerometer was inside a temperature controlled enclosure, so the bias was nearly constant for the entire aerobraking phase. The bias was calibrated using data from the 5 minute pre-entry margin phase. An automated spacecraft will have to check the bias value before each drag pass in order to obtain a good estimate of the drag delta-V, and a good estimate of the change in orbit period for that orbit. The accuracy of the prediction can be checked by comparing the prediction to the actual change computed by differencing the time of periapsis with the previous time of periapsis. Unfortunately, this check cannot be made until after the drag pass is over.

On-Board Navigation:

Work is underway to run the JPL Orbit Determination Program (ODP) that is currently run on the ground on-board a spacecraft. The most likely scenario is for the ODP to run on the computer that is part of a planned Electra payload which is being developed as part of a network infrastructure around Mars. The primary goal of that activity is to use the traditional doppler observable in order to autonomously update the arrival state for precision landing on Mars in near real time using assets orbiting Mars. The previous approach showed that very excellent timing predictions can be made with very simple algorithms using accelerometer data. Since the Simple Approach only predicts time, it is not useful for predicting either the altitude or the dynamic pressure on the next drag pass. Such predictions are needed to automate the propulsive corridor control maneuver. Although using the full ODP software is a complicated approach, if the ODP software is already running on-board for other reasons, then using the ODP for aerobraking would require the use of accelerometer data as an observable data type. Moriba Jah has been developing software that will enable the ODP to use accelerometer data as an observable.[16] He plans to test his modifications on the ground during the Odyssey aerobraking phase later this year (2001). This approach should result not only in the most accurate possible prediction of the time of the next periapsis, it should also predict the periapsis altitude well enough to determine when propulsive corridor control maneuvers are needed (at least when there are no major dust storms!). Hanna[15] has shown that a 4 by 4 and 5 by 5 gravity field is adequate for predicting the altitude of periapsis within 100 meters 3-9 orbits ahead. Being able to use a small degree and order gravity field will enable more rapid execution on-board.

Methods for Increasing the Timing Margin while Unloading the Reaction Wheels.

The final area of study is aimed not at predicting the time of periapsis, but at increasing the timing margin that is available. Increasing the timing margin enables very simple "periapsis detection" approaches to work at larger orbit periods, where the change in period, and thus the uncertainty in the time of the next periapsis, are larger. Increasing the available timing margin has the benefit of increasing the robustness of whatever timing prediction algorithm is used.

On the previous aerobraking missions, the timing margin was specified by the size of the deadband used for thruster control during the drag pass and the fact that the reference attitude was time-varying. Thruster control was used because no reaction wheel control algorithms were available. A time varying reference was used because the attitude change during the drag pass was larger than the deadband near the end of aerobraking. Johnson and Longuski[17] have evaluated several reaction wheel control algorithms which can be used during the drag phase of aerobraking. Staying on reaction wheels for the entire orbit reduces the propellant requirements of the mission not only by eliminating the thruster control phase, but also by using the aerodynamic moments to eliminate the thrusting required to unload the reaction wheels.

In order to use the reaction wheels during the drag pass, a different control mode must be used, because the aerodynamic moments during a drag pass can be much larger than the moments that the reaction wheels can provide. Most attitude control algorithms try to drive the difference between a reference attitude and the actual attitude to zero. This approach does not work when timing uncertainties create errors in the time varying reference attitude when aerodynamic moments are acting on the spacecraft. A further complication is that the aerodynamically stable attitude is not known exactly, at least not at the start of the aerobraking phase. All of these problems can be eliminated by detecting when the spacecraft is in the atmosphere, and then changing the control objective from minimizing an error relative to a specified reference attitude to something else, like minimizing the stored angular momentum.

During a drag pass, the desired attitude is such that there is zero angle of attack relative to the aerodynamically stable attitude. Trying to maintain any other attitude will result in aerodynamic moments which will cause the reaction wheels to spin up (or maybe down, if it is already spinning). A control system goal that minimizes the total system angular momentum not only drives the spacecraft toward the aerodynamically stable attitude, but also unloads any momentum stored in the reaction wheels "for free" during the drag pass. Atmospheric entry must be detected in order to switch from an inertial reference mode to a system momentum mode. Although the algorithms seem to work even for large angles of attack at entry, an actual implementation is expected to be similar to that of the previous missions, in that the sequence would turn the spacecraft to an inertially referenced attitude close to that desired at atmospheric entry and would not switch to the system momentum algorithm until atmospheric entry was actually detected. Although an accelerometer measurement could be used to trigger the switch from one mode to the next, the algorithms are being designed to use the system momentum (or the commanded torque to maintain the inertial reference) as the trigger, since that measurement will always be available. The return to an inertial reference would be controlled by a timer based on the orbital period. Shorter period orbits remain in the atmosphere longer, so the timer would need to be a function of orbit period. The orbit period could be determined by differencing the time of atmospheric entry from one orbit to the next. (If the accelerometer based orbit period is also computed, the two orbit periods could be compared.)

The algorithms that have been evaluated so far have been for one of the axes orthogonal to the "aerodynamically stable axis", i.e. for "pitch" or "yaw". In order to control the "roll" about the velocity vector, a different "spacecraft dependent" algorithm must be used. For example, for both Magellan and Mars Global Surveyor, the solar panels could articulate to change the aerodynamic moment about the velocity direction. Before the drag pass, the solar panels were put into a configuration that was supposed to make the aerodynamic moment about the "roll" axis zero. The system momentum algorithm would need to be able to make small adjustments to the solar panel gimbal positions in order to create a small change in the aerodynamic moment that would drive the angular momentum toward zero. The alternative would be to use thruster control on this axis, as was done for Magellan and MGS. For vehicles like the Mars Odyssey orbiter, which cannot articulate the solar panel when in the drag configuration, thruster control about the "roll" axis is a requirement, unless a special actuated flap is added.

Summary:

Previous missions have demonstrated that spacecraft behave as expected during the drag pass. The "looping" design of the Magellan sequencer for aerobraking showed that the same sequence of activities can be repeated over and over. All that is needed is a start time for each orbit, and the capability of writing sequences that can be timed "relative" to the start time. Relative timing within the sequence can be adjusted either by changing parameters, as was done for Magellan, or by uploading a new orbital skeleton sequence. Analysis of the MGS accelerometer data showed that this start time can be computed very accurately from the accelerometer data using very simple algorithms. Therefore, this technology is ready to be implemented on the next aerobraking mission.

Larger orbit periods require active estimation of the drag effects on the previous drag pass in order to predict the time of the next drag pass with a 5 minute accuracy because the period can change by many minutes or even hours. A simple polynomial function of orbit period times the integrated delta-V from the accelerometer provides an excellent estimate of the timing. The orbit period changes by only a few minutes for short orbit periods, so all that is needed is a means for determining the "center of the drag" in order to reset the timing prediction each orbit to prevent the timing error from accumulating. Since the active estimation of the drag works even better for short orbit periods, it can be used for the entire aerobraking phase, from the largest periods through to the shortest.

The robustness of these "autonomous timing" approaches can be increased by using the reaction wheel "stored momentum" algorithm to increase the timing margins, and thus reduce the chances of entering the atmosphere in an "unexpected" configuration or attitude. Using the reaction wheels for the entire orbit eliminates unnecessary thrusting, which saves propellant and reduces unmodelled perturbations to the orbit.

If the ODP software is running on-board, incorporating the accelerometer data as an observable enables the most accurate predictions . Even if the ODP is run on the ground, incorporating the accelerometer data will enable the most accurate reconstruction of the orbit, and will enable predictions to be made even if no tracking data is available, as long as the telemetry from the drag pass is down-linked.

Conclusions:

Aerobraking spacecraft should carry and use accelerometers to automate the sequence timing on-board the spacecraft. Simple algorithms have been developed to convert the integrated drag deceleration into a predicted change in the orbit period. The robustness of the automated sequence can be improved by using a newly developed attitude control law to increase the timing margins that are required to guarantee that a spacecraft will be properly configured and in the correct attitude prior to entering the atmosphere.

Since a significant fraction of the workload during Mars Global Surveyor aerobraking operations was associated with maintaining the sequence timing, automating the timing updates has the potential to significantly reduce the workload on the aerobraking operations team. Continuous 2-way tracking would not be critical if the sequence timing is automated. Automating the sequence timing will greatly reduce the required DSN tracking time. Since the DSN is an expensive resource, reducing the amount of dedicated, two-way tracking will significantly reduce the cost of the mission.

In order to fully automate the aerobraking process, the propulsive maneuvers that raise and lower the periapsis altitude to maintain an acceptable level of drag would also have to be automated. On the Magellan mission, these maneuvers were built into the sequence and triggered by a flag. Automating these maneuvers would require that the flag be set on-board the spacecraft, rather than by ground command. The Mars Global Surveyor mission showed that deciding when to perform a maneuver was more complicated for Mars Missions because both the periapsis altitude and the atmospheric density were more variable. A further complication is the large density increase that can accompany a moderate to large dust storm on Mars. Work is in progress to evaluate strategies for automating these propulsive maneuvers to safely aerobrake a spacecraft to a predetermined target orbit.

The Magellan and MGS missions both showed that cost saving design tradeoffs can be made to adapt existing hardware and software for aerobraking.

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